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(54) Abstract Title
Optical modulator

(57) An optical device (20) comprises a multilayer structure incorporating in sequence a silicon dioxide layer (22), a n+ doped silicon buried contact layer (24) and a silicon surface layer (26). The surface layer (26) is selectively etched back to form an exposed rib (28). An upper surface of the rib (28) is doped to form an elongate p+ electrode (30) along it. The surface layer (26) is selectively etched to the buried contact layer (24) in regions remote from the rib (28) to form two via channels (32a, 32b) for making electrical connection to the layer (24). The rib (28) forms a waveguide along which radiation propagates. Charge carriers are injected from the electrode (30) and the layer (24) into the rib (28), including a central region (34) of it, when the electrode (30) is biased at a higher potential than the layer (24). The charge carriers induce refractive index changes in the central region (34) in which a major part of the radiation propagating along the rib (28) is confined.

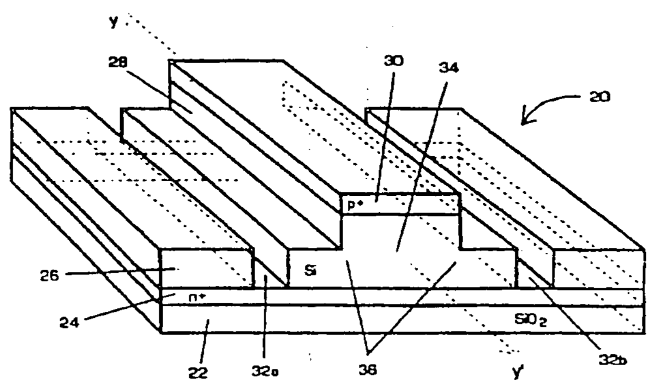

FIGURE 2

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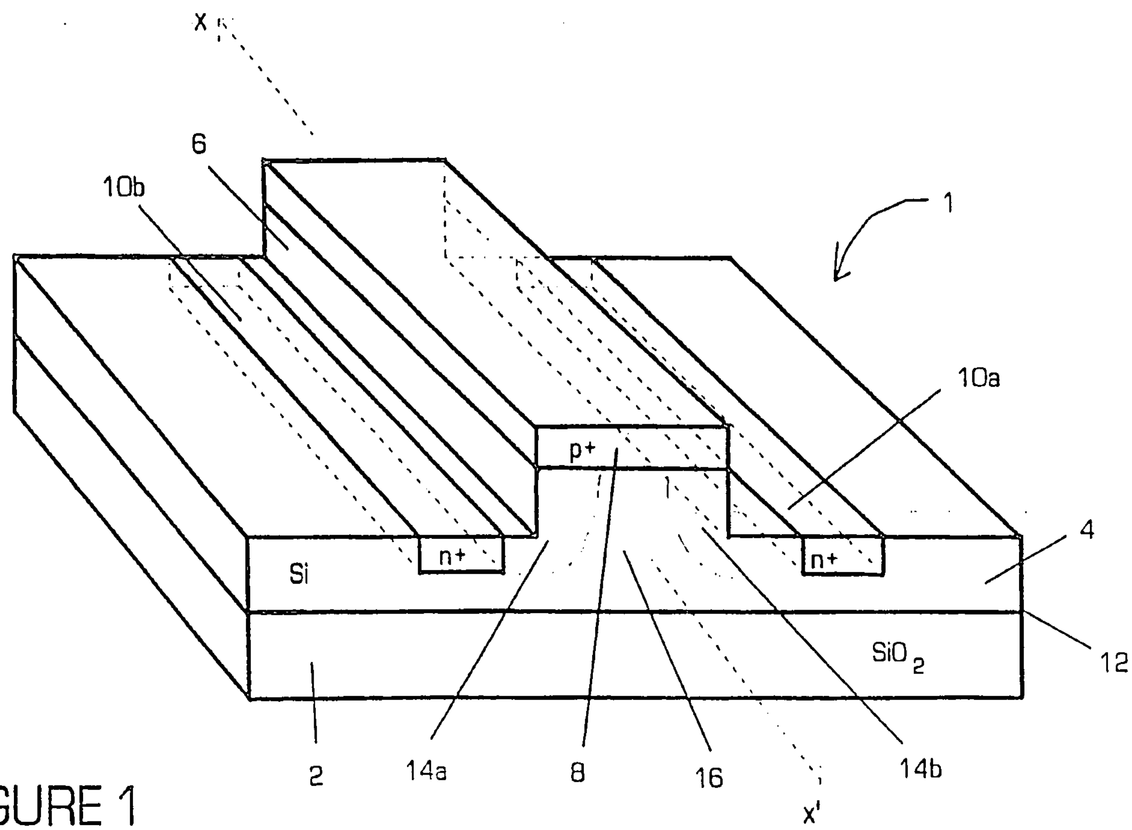

FIGURE 1
(Prior Art)

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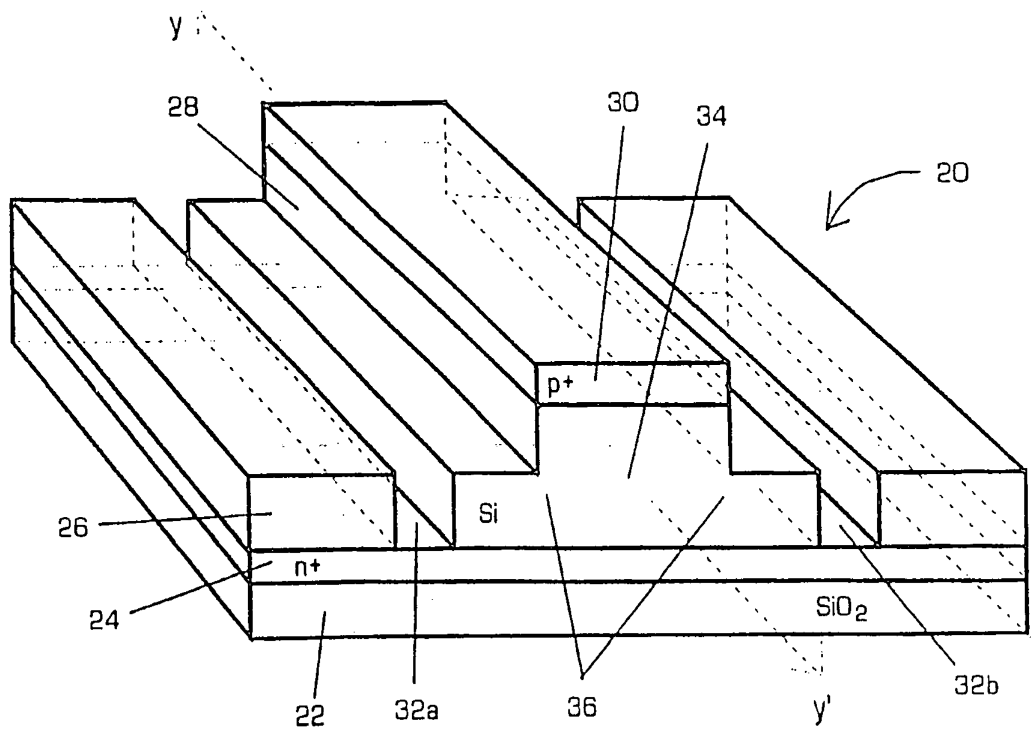

FIGURE 2

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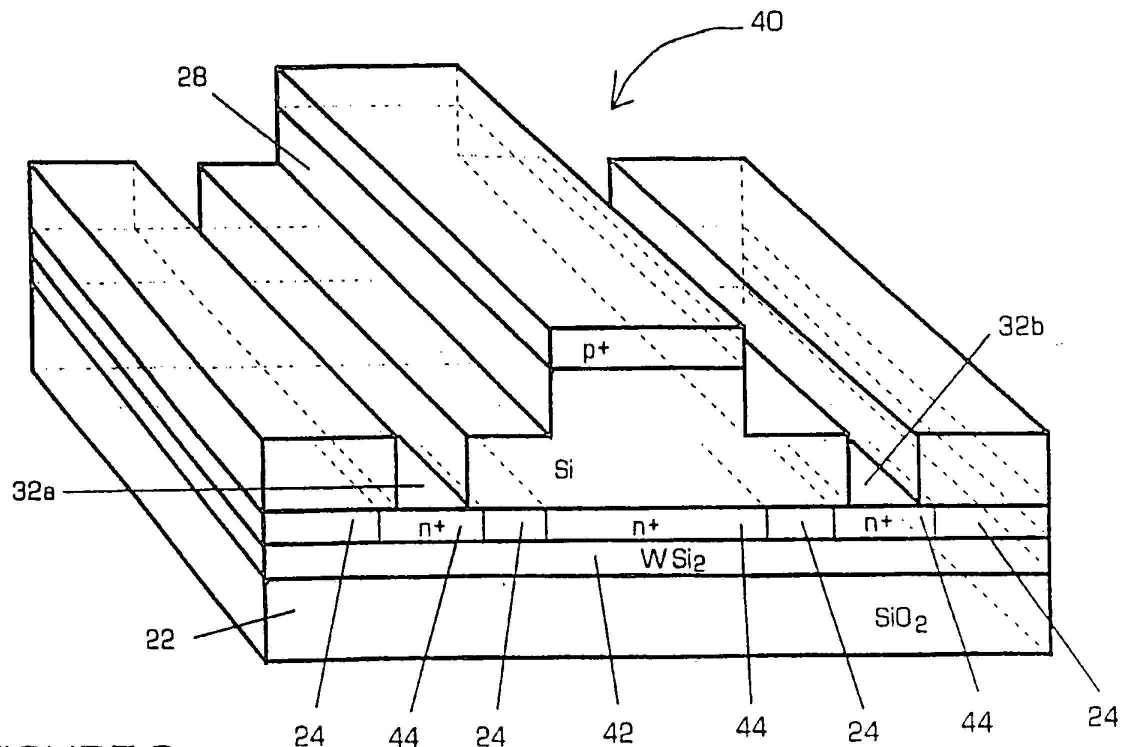

FIGURE 3

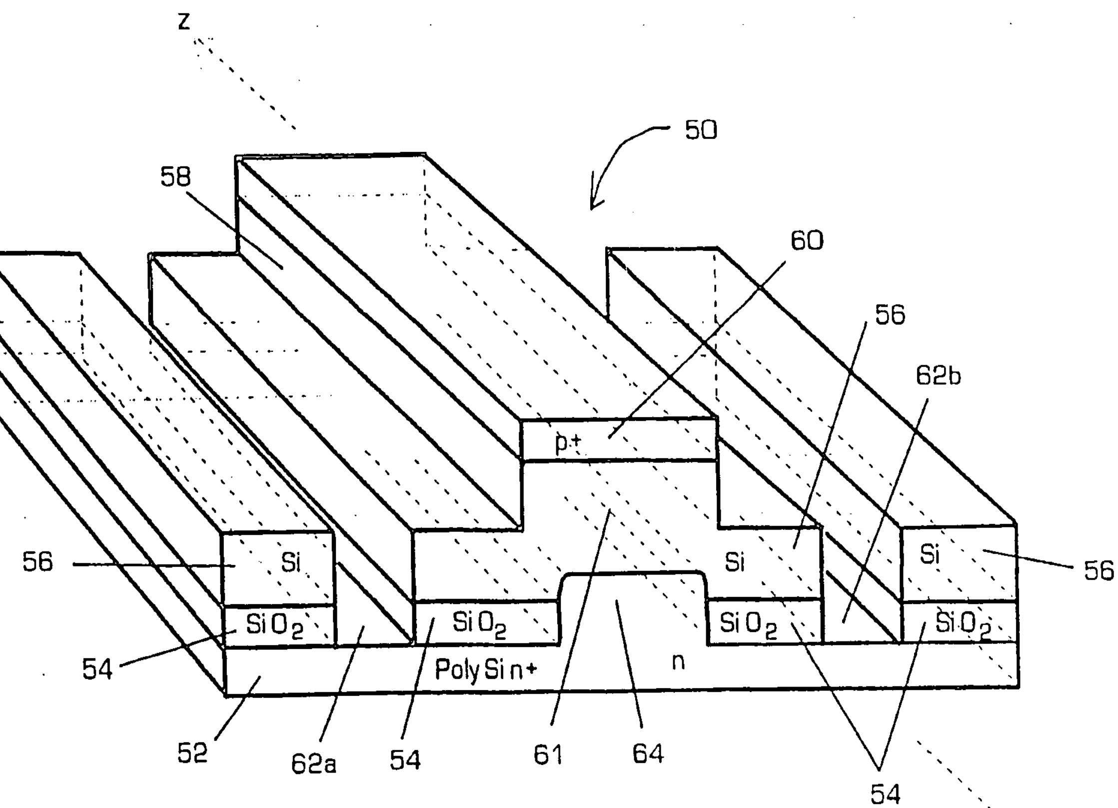
z
50
58
60
56
62b
p+
Si
Si
Si
56
56
SiO2
SiO2
SiO2
SiO2
54
Poly Si n+
n
52
62a
54
61
64
54
z'

FIGURE 4

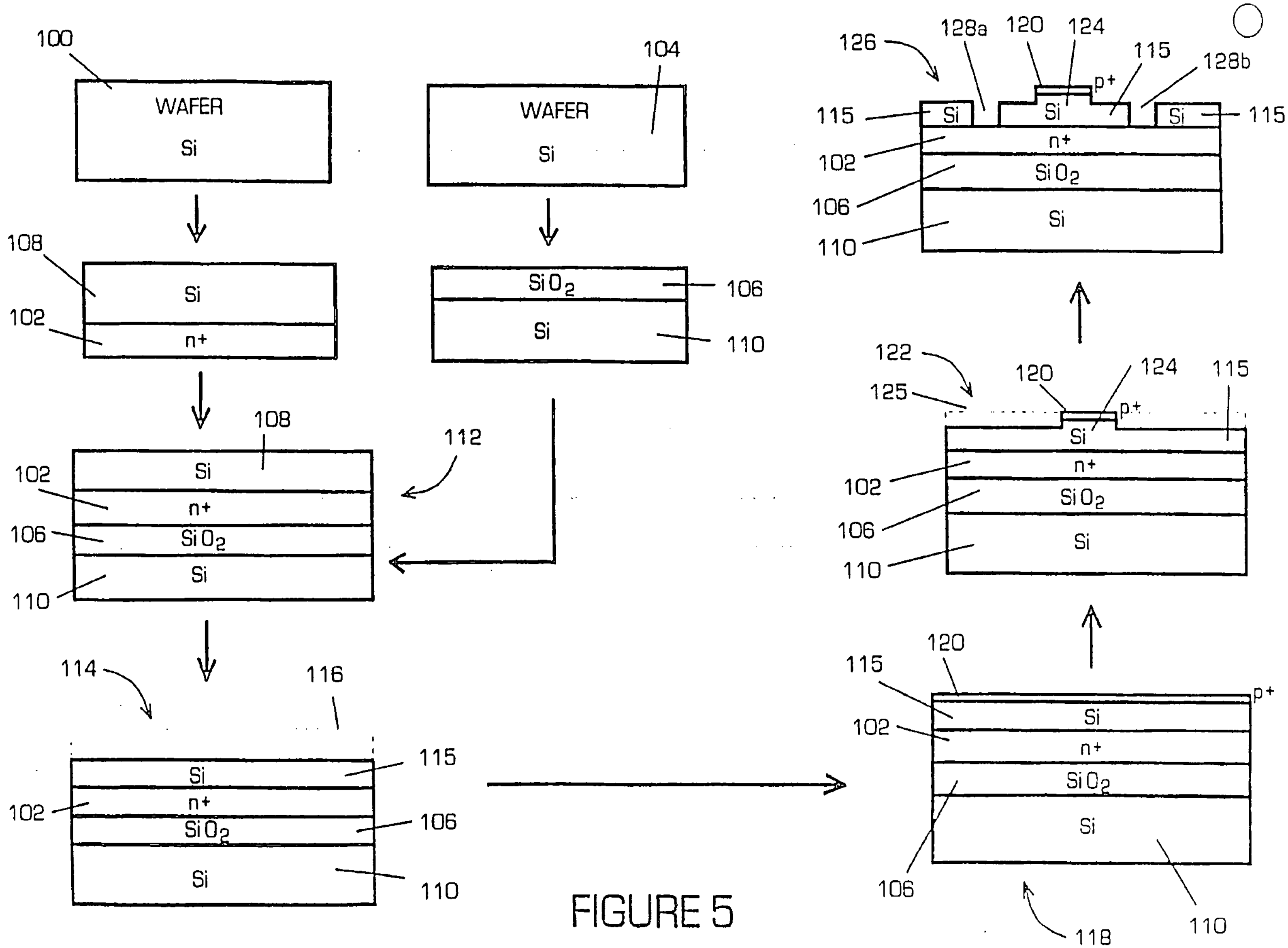
100
WAFER
Si
104
WAFER
Si
108
Si
102
n+
Si O2
106
Si
110
108
Si
102
n+
106
Si O2
Si
110
112
114
116
Si
115
102
n+
Si O2
106
Si
110
120
115
p+
Si
102
n+
Si O2
Si
106
110
118
122
125
120
124
115
p+
Si
102
n+
106
Si O2
Si
110
126
128a
120
124
115
128b
p+
115
Si
Si
Si
115
102
n+
106
Si O2
Si
110

FIGURE 5

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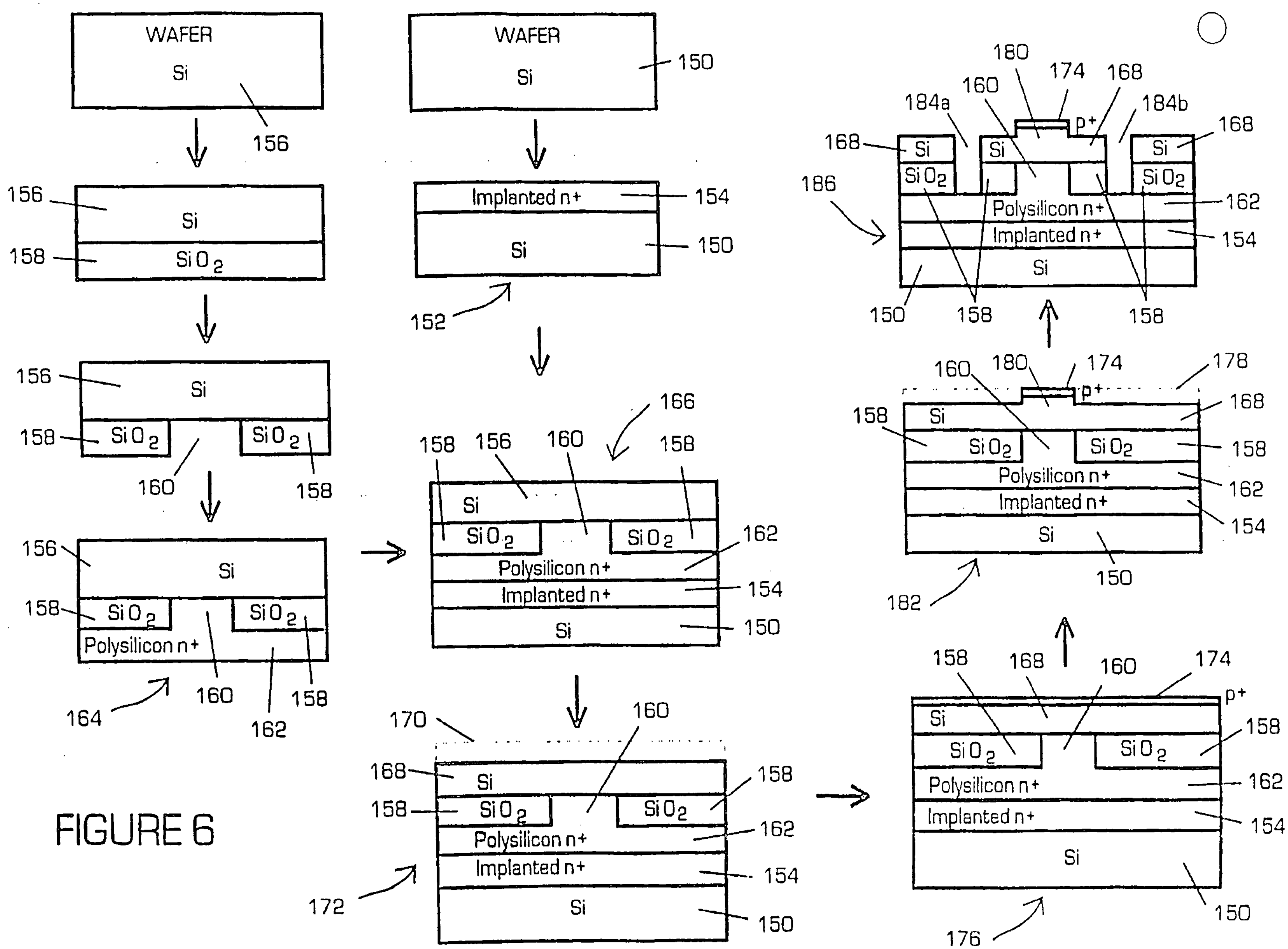
WAFER
Si
156
158
SiO2
160
Polysilicon n+
162
164
150
Implanted n+
154
152
166
168
170
172
174
p+
176
178
180
182
184a
184b
186

FIGURE 6

2323450

OPTICAL DEVICE

This invention relates to an optical device, and particularly but not exclusively to a device for modulating confined radiation in a waveguide.

Optical devices are well known in the prior art. They are described in a publication "Introduction to Semiconductor Integrated Optics" by H P Zappe (ISBN 0-89006-789-9, Artech House Publishers 1995). Optical devices for modulating radiation rely on their operation by exploiting optical properties of a modulating medium which are modifiable by external influences. One of the optical properties may include a refractive index. Induced changes in the refractive index may be anisotropic, where the medium becomes birefringent, or isotropic. There are many possible techniques for modulating the refractive index. These techniques are herewith described.

Refractive index changes may be induced in some optically transmissive materials by the application of an external mechanical force to them. This is referred to as the photo-elastic effect. Thermally induced refractive index changes are referred to as the thermo-optic effect.

Magnetically induced birefringence, referred to as a Faraday or magneto-optic effect, arises within some optically transmissive materials when subjected to a magnetic field. Factors such as magnetic flux density, a Verdet constant of the materials, composition of the materials and radiation propagation path length within the materials determine the magnitude of birefringence attainable.

Refractive index changes may be induced in some materials by application of an electric field to them. These refractive index changes occur due to both the Kerr and the Pockels effect. Refractive index changes arising from the Kerr effect are proportional to the Kerr constant of the materials and the square of the electric field applied to them. For the Pockels effect, refractive index changes are proportional to the applied electric field. The Pockels effect is only observed in crystalline materials comprising crystals which lack a centre of symmetry.

Refractive index changes may also be induced in some materials by introducing free charge carriers into them. Such changes are referred to as free carrier modulation or sometimes as the plasma dispersion effect. The free carriers modify both real and imaginary parts of the refractive index, thereby introducing both optical phase shift and optical absorption to optical radiation propagating through regions of these materials in which the carriers are present.

Silicon has a centro-symmetric crystalline structure and therefore does not exhibit the Pockels effect, except when high temperature poling is applied in which case a weak effect is obtained. This weak effect corresponds to a coefficient r of 10^{-12} m V^{-1} in equation [1] which describes a change in refractive index Δn as a function of silicon refractive index n_0 and applied electric field E:

$$\Delta n = \frac{1}{2} n_0^3 r E \qquad [1]$$

Silicon weakly exhibits the Kerr effect for very high electric field strengths, for example refractive index changes of approximately 10^{-4} are attainable for applied electric field strengths of 10^6 V m^{-1}. In order to provide a practicable optical device for modulating radiation based upon a silicon waveguide, either the thermo-optic effect or the plasma dispersion effect have to be exploited. Operating bandwidths of devices relying on the thermo-optic effect in a silicon waveguide are restricted by relatively slow thermal dynamics of the waveguide; bandwidths of tens of kilohertz may be attained in practice for power inputs amounting to several Watts. Conversely, operating bandwidths of devices relying on the plasma dispersion effect in a silicon waveguide are restricted by rapidity of removal and injection of charge carriers from a region thereof in which optical radiation propagates; such devices may provide operating bandwidths of several tens of megahertz in practice. These bandwidths may be increased by reducing charge carrier lifetime in the region. This is achieved by doping it with gold and thereby providing more carrier recombination sites therein.

Optical radiation propagating within a waveguide has an electric field vector of a magnitude E which varies spatially along the waveguide at an instance of time

according to equation [2]:

$$E \propto e^{ikx} \qquad [2]$$

in which
k is a wavenumber of the optical radiation; and
x is a distance along the waveguide.

The wave number k in equation [2] is expressible as a product of a free-space wavenumber k_o for the optical radiation and the refractive index n of silicon according to equation [3]:

$$E \propto e^{ink_o x} \qquad [3]$$

In equation [3], the refractive index n may be expressed in terms of a real part n_r and an imaginary part α according to equation [4]:

$$n = n_r + i\alpha \qquad [4]$$

from which the magnitude of the electric field strength E is expressed according to equation [5]:

$$E \propto e^{in_r k_o x} e^{-\alpha k_o x} \qquad [5]$$

Injection of free carriers into the waveguide modifies both the real part n_r and imaginary part α of the refractive index n of the waveguide which are interrelated according to the Kramers-Kronig relationship which is expressed in equations [6] and [7]:

$$\Delta n_r = -\frac{q^3\lambda^2}{4\pi^2 c^3 n_r \varepsilon_o}\left(\frac{N_e}{m_{ce}^2\mu_e} + \frac{N_h}{m_{ch}^2\mu_h}\right) \quad [6]$$

$$\Delta\alpha = -\frac{q^2\lambda^2}{8\pi^2 c^2 n_r^2 \varepsilon_o}\left(\frac{N_e}{m_{ce}} + \frac{N_h}{m_{ch}}\right) \quad [7]$$

in which

c is the speed of light in vacuum;

μ_e is an electron mobility within silicon;

μ_h is an hole mobility within silicon;

m_{ce} is an effective mass of a free electron within silicon;

m_{ch} is an effective mass of a free hole within silicon;

q is the charge on an electron;

λ is a wavelength of radiation propagating along the waveguide;

N_e is a free electron concentration within the waveguide;

N_h is a free hole concentration within the waveguide;

Δn_r is a change in the real part n_r;

$\Delta\alpha$ is a change in the imaginary part α; and

ε_o is the permittivity of free space.

For silicon, changes to the real part n_r of approximately 10^{-4} may be induced for applied electric field strengths of 10^8 V m^{-1} for optical radiation of 1 μm wavelength. Accompanying changes to the imaginary part are an order of magnitude smaller than this.

Prior art optical devices for modulating radiation based on a silicon waveguide generally exploit the plasma dispersion effect. Such devices employ a silicon p-i-n diode structure fabricated using standard silicon micromachining techniques. The structure comprises an electron acceptor doped p region, an intrinsic i region in the form of a rib and an electron donor doped n region. Optical radiation is confined to the intrinsic i region which functions as the waveguide. Charge carriers are injected

into the intrinsic i region from the p and n regions when the p region is biased at a higher potential than the n region. The carriers modulate the refractive index of the waveguide.

The p and n regions in the prior art devices are fabricated adjacent to the rib and along a top region of it. As a consequence of this, most of the carriers injected are concentrated near to edge regions of the rib and few carriers are found in a central region of it. A majority of radiation confined within the waveguide propagates in the central region and therefore interaction between the radiation and the charge carriers injected is inefficient because they are partially isolated from one another. This is a major disadvantage in the prior art devices because the charge carriers are used inefficiently. This means that more charge carriers have to be injected to achieve a desired degree of modulation than is necessary compared to a device in which the carriers are concentrated in the central region. Recombination times for excess inefficiently employed carriers in the prior art devices limit their achievable modulating bandwidth.

A small phase change is induced by the injected charge carriers in the radiation propagating in the prior art devices. This phase change is converted into an amplitude change by incorporating at least one device into a Mach-Zehnder interferometer.

It is an object of the invention to provide an alternative optical device.

The invention provides an optical device incorporating waveguiding means for confining and guiding radiation and charge carrier injecting means for modulating refractive index of the waveguiding means wherein the injecting means is arranged to inject charge carriers predominantly into regions of the waveguiding means in which the radiation predominantly propagates.

The invention provides the advantage that carriers injected into the waveguiding means modulate the refractive index thereof more efficiently compared to prior art devices.

In the device of the invention, the injecting means may comprise n and p doped electrode means arranged on opposing sides of the waveguiding means for injecting charge carriers predominantly into regions of the waveguiding means in which radiation predominantly propagates. At least one of the electrode means may be a buried conducting layer for ensuring that injected charge carriers interact with the radiation effectively. The buried layer may incorporate a metal silicide layer for ensuring low resistance connection to the electrode means and thereby increasing modulation bandwidth. The silicide layer may incorporate tungsten silicide.

The device may incorporate the waveguiding means in the form of a rib waveguide of doped silicon and the injecting means in the form of p and n doped regions of silicon arranged on opposing sides of the waveguide for injecting charge carriers predominantly into regions of the waveguide in which radiation predominantly propagates. This has the advantage that charge carriers injected from the n and p doped regions are concentrated in a central region of the waveguide whereat they interact efficiently with radiation propagating in the waveguide. The p and n doped regions may incorporate dopant impurities to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. The waveguide may be gold doped for reducing carrier lifetime and increasing recombination site density therein thereby increasing modulation bandwidth. The device may comprise a thermally bonded wafer couplet for providing the buried layer.

In order that the invention might be more fully understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings in which:-

Figure 1 is a schematic perspective view of a prior art plasma dispersion optical modulator;

Figure 2 illustrates in perspective an optical device of the invention;

Figure 3 is a schematic perspective view of an optical device of the invention incorporating a buried tungsten silicide layer;

Figure 4 illustrates in perspective an optical device of the invention incorporating a polysilicon n+ doped conduction layer and an associated elongate n+ doped electrode region;

Figure 5 illustrates stages in a microfabrication process for producing the optical device in Figure 2; and

Figure 6 illustrates stages in a microfabrication process for producing the optical device in Figure 4.

Referring to Figure 1 there is shown a schematic view of a prior art plasma dispersion optical modulator indicated generally by 1. It incorporates a silicon dioxide (SiO_2) layer 2 and a silicon surface layer 4. The surface layer 4 and the silicon dioxide layer 2 are parallel, overlaid and unitary. The surface layer 4 is low doped silicon with less than 10^{16} atoms cm^{-3} impurity atom density.

The surface layer 4 is etched back to form an exposed rib 6. A reference axis x-x' is included in Figure 1 and is orientated in a direction along the rib 6. The rib 6 is doped along its upper surface to form an elongate p+ electrode 8. An exposed surface of the surface layer 4 is doped to produce two elongate n+ electrodes 10a, 10b which are formed into the surface layer 4. The n+ electrodes 10a, 10b are adjacent at respective sides of the rib 6 but do not encroach onto it. The p+ electrode 8, the n+ electrodes 10a, 10b and the rib 6 are all aligned parallel to one another. An interface 12 is formed between the silicon dioxide layer 2 and the surface layer 4.

The electrodes 8, 10a, 10b are doped with impurities to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. The n+ electrodes 10a, 10b are doped with phosphorus and the p+ electrode 8 is doped with boron.

The electrodes 8, 10a, 10b are 2.5 mm long in a direction along the reference axis x-x' which is parallel to the rib 6. The rib 6 is 4 μm wide in a direction orthogonal to the axis x-x' and parallel to the surface layer 4. It is 6.5 μm high from the interface 12 in a normal direction therefrom. The surface layer 4 is 3.3 μm thick in a normal

direction to the interface 12 in regions remote from the rib 6. The electrodes 10a, 10b are 5 μm wide in a direction orthogonal to the axis x-x' and parallel to the surface layer 4. They are 0.5 μm deep in a normal direction to the exposed surface of the surface layer 4.

Operation of the prior art optical modulator 1 will now be described with reference to Figure 1. The rib 6 forms a monomode optical waveguide along which radiation of wavelength in a range of 1.3 μm to 1.5 μm, in particular radiation of 1.3 μm and 1.5 μm wavelength which is often employed in optical communication systems, propagates with low loss of less than 1 dB cm^{-1}. The radiation is confined within this waveguide by virtue of differing refractive indices of the rib 6, the silicon dioxide layer 2 and a low dielectric constant medium such as air or cladding film (not shown) surrounding the modulator 1.

The electrodes 8, 10a, 10b and the rib 6 form a p-i-n diode. When a potential difference is applied to bias the p+ electrode 8 at a higher potential than the n+ electrodes 10a, 10b, the p-i-n diode becomes forward biased and charge carriers are injected into the waveguide. The electrodes 8, 10a, 10b are configured such that the potential difference results in generation of an electric field which is concentrated in edge regions 14a, 14b relative to a central region 16 of the rib 6. As a result of this, charge carriers injected from the electrodes 8, 10a, 10b are concentrated principally in the edge regions 14a, 14b. In consequence, a greater change of refractive index occurs due to the plasma-dispersion effect in the edge regions 14a, 14b relative to the central region 16. Optical radiation propagating in the waveguide is mainly confined to the central region 16 and is therefore only weakly affected by the injected carriers in the edge regions 14a, 14b.

The charge carriers injected into the rib 6 result in refractive index changes therein and thereby phase modulation of the optical radiation propagating along it. This phase modulation is converted into amplitude modulation of the optical radiation by incorporating the modulator 1 into one arm of a Mach-Zehnder interferometer (not shown).

Referring now to Figure 2, an optical device of the invention indicated generally by 20 comprises in sequence a silicon dioxide layer 22, a n+ doped silicon buried contact layer 24 and a silicon surface layer 26. The layers 22, 24, 26 are parallel, overlaid and unitary.

The surface layer 26 is etched to form an exposed rib 28. A reference axis y-y' is included in Figure 2 and is orientated in a direction along the rib 28. An upper surface of the rib 28 is doped to form an elongate p+ electrode 30. The electrode 30 and the rib 28 are aligned parallel to one another. The surface layer 26 is selectively etched in regions remote from the rib 28 to form two via channels 32a, 32b for making electrical connection to the buried contact layer 24. Electrical connection is achieved by depositing doped polysilicon or metal tracks (not shown) into the channels 32a, 32b.

The p+ electrode 30 is doped with boron to an impurity concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. The rib 28 is 4 μm wide in a direction orthogonal to the axis y-y' and parallel to the surface layer 26. It is 6.5 μm high from the buried contact layer 24 in a normal direction therefrom. The surface layer 26 is 3.3 μm thick in a direction normal to the buried contact layer 24 in regions remote from the rib 28. The contact layer 24 is 0.1 μm thick and is doped with an electron donor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. The silicon dioxide layer 22 is at least 1 μm thick for reducing leakage loss of optical radiation along the rib 28.

The operation of the device 20 will now be described. The rib 28 forms a waveguide along which optical radiation of wavelength in a range of 1.3 μm to 1.5 μm propagates, in particular radiation of 1.3 μm and 1.5 μm wavelength which is often employed in optical communication systems. The radiation is confined within the waveguide by a difference in refractive index between the rib 28, the buried contact layer 24, the silicon dioxide layer 22 and a low dielectric constant medium surrounding the device 20.

When a potential difference is applied to bias the p+ electrode 30 at a higher potential than the buried contact layer 24, charge carriers are injected predominantly into a central region 34 of the rib 28. A charge distribution is thereby generated where

there is a greater concentration of the carriers in the central region 34 in which a majority of the optical radiation is confined in comparison to edge regions 36 of the rib 28. The carriers injected into the waveguide thereby efficiently modulate the radiation in comparison to the prior art modulator 1 in Figure 1. In the device 20, the injected carriers provide phase modulation of the radiation within the waveguide. This phase modulation is converted to amplitude modulation by inserting the device 20 into one arm of a Mach-Zehnder interferometer (not shown) in a similar manner to the prior art modulator 1.

Referring now to Figure 3, an alternative optical device of the invention is indicated by 40. It is identical to the device 20 in Figure 2 except that a buried tungsten silicide layer (W Si_2) 42 is included between the silicon dioxide layer 22 and the buried contact layer 24, and the layer 24 is selectively doped in regions 44 near the channels 32a, 32b and the rib 28. The silicide layer 42 is 100 nm thick.

The tungsten silicide layer 42 has a greater conductivity than the buried contact layer 24. It reflects optical radiation efficiently, thereby providing improved confinement of radiation within the rib 28. Moreover, the silicide layer 42 also provides a lower resistance connection to all regions of the contact layer 24 thereby enhancing high frequency modulating performance of the device 40. The regions 44 in the buried layer 24 are formed by selectively implanting a dopant into the silicide layer 42 and then subsequently diffusing the dopant into the contact layer 24 after wafer bonding which will be described later.

Another optical device of the invention is indicated by 50 in Figure 4. It comprises in sequence a polysilicon n+ phosphorus doped conduction layer 52, a silicon dioxide insulating buried layer 54 and a silicon surface layer 56. The surface layer 56 is low doped silicon with an impurity concentration of less than 10^{16} atoms cm^{-3}. It is etched back to form an exposed rib 58. A reference axis z-z' is included in Figure 4 and is orientated in a direction along the rib 58. An upper surface of the rib 58 is doped with boron impurity to form an elongate p+ electrode 60. The rib 58 and the p+ electrode 60 are aligned parallel to one another. A central region 61 of the rib 58 is situated beneath the p+ electrode 60. Via channels 62a, 62b are remote from the rib 58 and are formed by etching through the surface layer 56 and the buried layer 54 to the

conduction layer 52 to enable electrical connection to be made to it. Electrical connection to the conduction layer 52 is achieved by depositing doped polysilicon or metal tracks into the via channels 62a, 62b. An elongate n+ doped electrode region 64 is formed by selectively etching through the insulating buried layer 54 and a short distance of 0.5 μm into the surface layer 56 to form a channel in which doped polysilicon of the layer 52 is deposited. The electrode region 64 is aligned along the axis z-z' and is situated on an opposite side of the central region 61 relative to the p+ electrode 60. The rib 58 is a monomode waveguide for confinement of optical radiation of wavelength in a range of 1.3 μm and 1.5 μm, in particular radiation of 1.3 μm and 1.5 μm wavelength which is often employed in optical communication systems.

The conduction layer 52 and p+ electrode 60 are doped with impurity atoms to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. The rib 58 is identical in size to the rib 28 illustrated in Figure 3. The surface layer 56 is 3.3 μm thick in regions remote from the rib 58.

When a potential difference is applied to bias the p+ electrode 60 at a higher potential than the electrode region 64, charge carriers are injected into the central region 61. The electrode region 64 is truncated widthwise to ensure that injected charge carriers are predominantly confined to the region 61 and thereby efficiently modulate its refractive index. Because of this confinement, interelectrode capacitance between the p+ electrode 60 and electrode region 64 is less in the device 50 in comparison to interelectrode capacitance of the modulator 1 and the devices 20, 40 for achieving an equivalent change in refractive index of the rib 6, 28. This relatively smaller interelectrode capacitance provides an enhanced operating bandwidth for the device 50 in Figure 4.

Referring now to Figure 5, there is shown schematically stages in a microfabrication process for producing the device 20. A polished low doped silicon wafer 100 containing a dopant impurity to a concentration of less than 10^{16} atoms cm^{-3} is exposed to ion implantation to form a heavily n+ doped layer 102 on one side of it. The layer 102 contains a dopant impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. A second polished low doped silicon wafer 104 is thermally oxidised to

form a thick silicon dioxide surface layer 106 on one side of it. Layers 108, 110 correspond to low doped silicon regions of the wafers 100, 104 respectively. The layers 102, 106 are then thermally bonded together at a high temperature of 1100 °C in an atmosphere of wet oxygen and nitrogen such that they fuse together to form a wafer couplet indicated by 112. The atmosphere is created by mixing oxygen, hydrogen and nitrogen gases which spontaneously react at the high temperature to form a gaseous mixture of steam, oxygen and nitrogen. The couplet 112 is then polished to form a thinned wafer couplet indicated by 114 in which the layer 108 is polished to remove material as indicated by a dashed line 116 to form a thinned layer 115. Next, the couplet 114 is exposed to ion implantation to form a heavily doped p+ surface layer 120 with an impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}, thereby producing a wafer couplet indicated by 118. Standard microfabrication lithographic and dry etching processes are then employed to etch the layers 115, 120 to form a rib 124 in a wafer couplet indicated by 122. A dashed line 125 indicates an amount of material removed during formation of the rib 124. Next, via channels 128a, 128b are formed by using standard lithographic and etching processes, thereby producing a wafer couplet indicated by 126. Further processing stages (not shown) on the couplet 126 include metal track deposition for electrical connection to the n+ doped layer 102 and to the p+ surface layer 120 remaining to provide a completed optical device.

Fabrication of the device 40 in Figure 3 is similar to the device 20 in Figure 2 except that the tungsten silicide layer 42 is deposited prior to bonding wafers to form a couplet.

The process shown schematically in Figure 5 is known as "Bond and Etchback Silicon on Insulator" (BESOI). It has not been used in the prior art for fabrication of optical devices for modulating radiation.

Referring now to Figure 6, there is shown schematically stages of a microfabrication process for producing the device 50. A low doped silicon wafer 150 containing a dopant impurity of concentration less than 10^{16} atoms cm^{-3} is exposed to phosphorus dopant implantation to form a wafer indicated by 152 incorporating an implanted n+ surface layer 154 on it. The layer 154 contains dopant to a concentration in a range

of 10^{18} to 10^{19} atoms cm^{-3}. A low doped silicon wafer 156 is oxidised to form a 1 μm thick surface silicon dioxide layer 158 onto it. A channel 160 is etched into the silicon dioxide layer 158 by employing standard microfabrication lithography and dry etching techniques. A doped polysilicon n+ layer 162 is then deposited onto the silicon dioxide layer 158 and into the channel 160. An exposed external surface of the layer 162 is then polished to planarise it to form a wafer indicated by 164. The wafers 152, 164 are abutted with the surface layer 154 contacting the polysilicon n+ layer 162 and then thermally bonded at a high temperature of 1100 °C in an atmosphere of wet oxygen and nitrogen to form a wafer couplet indicated by 166. The atmosphere is created by mixing oxygen, hydrogen and nitrogen gases which spontaneously react at the high temperature to form a gaseous mixture of steam, oxygen and nitrogen. The couplet 166 is polished to thin the wafer 156 contained therein to form a layer 168 where a dashed line 170 indicates a quantity of material removed by polishing to form a couplet indicated by 172. The layer 168 of the couplet 172 is exposed to boron impurity implantation to form a doped p+ surface layer 174 to provide a wafer couplet indicated by 176. The layer 168 is doped with boron impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}. By employing standard lithographic and dry etching techniques, the surface layer 174 and the layer 168 are etched back as indicated by a dashed line 178 except in an area to form a rib 180, thereby providing a wafer couplet indicated by 182. Two connection via channels 184a, 184b are then delineated and etched through the layers 158, 168 to provide a couplet indicated by 186. Further processing stages (not shown) on the couplet 186 include metal track deposition for electrical connection to the n+ layer 162 and to the p+ surface layer 174 remaining to provide a completed optical device.

The ribs 28, 58 in Figures 2, 3 and 4 may be gold doped in order to increase device operating bandwidth by ensuring rapid removal of charge carriers by recombination. As an alternative to gold doping, charge carrier recombination within the ribs 28, 58 may be increased by forming lattice defects therein which function as recombination sites. Such defects may be introduced by exposing the ribs 28,58 to high power laser or electron beams which create localised thermal stresses therein and thereby defects therein. Alternatively, the ribs 28, 58 may be exposed to intense neutron beams for introducing the defects.

In Figures 2, 3 and 4, dopant types may be swapped, namely n+ doped and p+ doped regions become p+ doped regions and n+ regions respectively, to provide alternative optical devices of the invention. This does not affect their mode of operation other than reversing polarity of applied potential required for injecting charge carriers into the rib 28, 58, 124, 180. Although thermal bonding of wafers at a temperature of 1100 °C is described above, satisfactory bonding may be achieved in a range of temperatures from 800 °C to 1200 °C. Although provision of the atmosphere of wet oxygen and nitrogen described above may improve bonding strength, it is not essential for achieving a thermal bond between wafers. The bond is sufficiently robust to survive further high temperature processing steps, for example steps necessary for integrating electronic circuits onto the wafers. Other methods of bonding may also be used to fabricate the device instead of employing thermal bonding.

Electronic circuits may be monolithically integrated with the devices 20, 40, 50. These circuits may comprise, for example, buffer amplifiers and logic gates. The circuits may be fabricated after formation of the rib 28, 58, 124, 180. Alternatively, the circuits may be formed prior to formation of the rib 28, 58, 124, 180 and may be protected from etching in a similar manner to which the rib itself is protected during etching, for example by a resist layer or a metallic masking layer which is later removed by processes such as sputtering, plasma etching or wet chemical etching.

The devices 20, 40, 50 may also be fabricated by using epitaxial layer deposition processes such as SIMOX, thereby avoiding a requirement to bond wafers together.

Although the rib waveguide 28, 58, 124, 180 incorporates dopant impurity to a concentration of less than 10^{16} atoms cm^{-3}, the concentration may be increased above 10^{16} atoms cm^{-3} with a consequence that radiation absorption within the device 20, 40, 50,126, 186 increases correspondingly.

CLAIMS

1. An optical device incorporating waveguiding means for confining and guiding radiation and charge carrier injecting means for modulating refractive index of the waveguiding means wherein the injecting means is arranged to inject charge carriers predominantly into regions of the waveguiding means in which the radiation predominantly propagates.

2. A device according to Claim 1 wherein the injecting means comprises n and p doped electrode means arranged on opposing sides of the waveguiding means for injecting charge carriers predominantly into regions of the waveguiding means in which radiation predominantly propagates.

3. A device according to Claim 2 wherein the waveguiding means comprises a rib waveguide of doped silicon.

4. A device according to Claim 2 or 3 wherein the electrode means includes a buried conducting layer.

5. A device according to Claim 4 wherein the buried layer incorporates a metal silicide layer.

6. A device according to Claim 5 wherein the silicide layer contains tungsten silicide.

7. A device according to Claim 5 or 6 wherein the silicide layer is selectively predoped with impurity which is arranged to diffuse therefrom during fabrication of the device for reducing series connection resistance to the buried layer and to the waveguiding means.

8. A device according to any one of Claims 2 to 7 wherein the electrode means incorporate dopant impurities to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

9. A device according to any one of Claims 2 to 8 wherein the waveguiding means is gold doped for reducing carrier lifetime and increasing recombination site density therein.

10. A device according to any one of Claims 2 to 9 wherein the waveguiding means incorporates induced lattice defects for reducing carrier lifetime and increasing recombination site density therein.

11. A device according to Claim 10 wherein the defects in the waveguiding means are at least one of electron, laser or neutron irradiation induced.

12. A device according to any one of Claims 4 to 11 comprising a thermally bonded wafer couplet for providing the buried layer.

13. A device according to any one of Claims 4 to 12 incorporating connecting means for making electrical connection to the buried layer.

14. A device according to Claim 13 wherein the connecting means comprise one or more via channels adjacent to the waveguide.

15. A device according to any preceding claim wherein the waveguiding means incorporates dopant impurity to a concentration of less than 10^{16} atoms cm^{-3}.

16. A device according to any preceding claim wherein electronic circuits are monolithically integrated with it.

17. A device according to Claim 1 wherein the injecting means comprises a doped silicon buried contact layer and an electrode layer, the waveguiding means comprises a rib waveguide, and the device is a multilayer structure incorporating in sequence a silicon dioxide layer, the contact layer, and a silicon surface layer incorporating the rib waveguide with the electrode layer thereon.

18. A device according to Claim 17 wherein the silicon dioxide layer is at least 1 μm thick.

19. A device according to Claim 17 or 18 wherein the buried contact layer incorporates dopant impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

20. A device according to Claim 17, 18 or 19 wherein the buried contact layer incorporates a metal silicide layer.

21. A device according to Claim 20 wherein the silicide layer contains tungsten silicide.

22. A device according to any one of Claims 17 to 21 wherein the electrode layer incorporates dopant impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

23. A device according to any one of Claims 17 to 22 wherein the silicon surface layer incorporates dopant impurity to a concentration of less than 10^{16} atoms cm^{-3}.

24. A device according to any one of Claims 17 to 23 wherein the waveguide is gold doped for increasing recombination site density and reducing carrier lifetime therein.

25. A device according to any one of Claims 17 to 24 wherein the waveguide incorporates induced lattice defects for reducing carrier lifetime and increasing recombination site density therein.

26. A device according to Claim 25 wherein the defects in the waveguide are at least one of electron, laser or neutron irradiation induced.

27. A device according to Claim 1 wherein the injecting means comprises a doped polysilicon layer and an electrode layer, the waveguiding means comprises a rib waveguide, and the device is a multilayer structure incorporating in sequence the doped polysilicon layer, a silicon dioxide layer and a silicon surface layer incorporating the rib waveguide with the electrode layer thereon.

28. A device according to Claim 27 wherein the polysilicon layer is arranged to contact the silicon surface layer only in a region coincident with the waveguide for reducing device interelectrode capacitance.

29. A device according to Claim 27 or 28 wherein the polysilicon layer incorporates dopant impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

30. A device according to Claim 27, 28 or 29 wherein the electrode layer incorporates dopant impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

31. A device according to any one of Claims 27 to 30 wherein the surface layer incorporates dopant impurity to a concentration of less than 10^{16} atoms cm^{-3}.

32. A device according to any one of Claims 27 to 31 wherein the waveguide is gold doped for increasing recombination site density and reducing carrier lifetime therein.

33. A device according to any one of Claims 27 to 32 wherein the waveguide incorporates induced lattice defects for reducing carrier lifetime and increasing recombination site density therein.

34. A device according to Claim 33 wherein the defects in the waveguide are at least one of electron, laser or neutron irradiation induced.

35. A method for fabricating an optical device, the method including the steps of:
(a) providing first and second doped silicon wafers;
(b) doping the first wafer with impurity to form an electrode surface layer upon it;
(c) depositing a silicon dioxide surface layer onto the second wafer;
(d) bonding the wafers together at the electrode surface layer and the silicon dioxide layer by using a bonding process to form a wafer couplet;
(e) polishing the first wafer in the couplet to provide a thinned doped silicon surface layer adjoining the electrode surface layer;
(f) doping the thinned silicon layer with impurity to form a doped electrode layer thereon;
(g) etching selectively into the doped electrode layer and the thinned silicon layer to delineate a rib waveguide therein; and
(h) etching selectively one or more via connection channels through the thinned silicon layer for making electrical connection to the electrode surface layer.

36. A method according to Claim 35 wherein in step (a) the wafers have a dopant concentration of less than 10^{16} atoms cm^{-3}.

37. A method according to Claim 35 or 36 wherein in step (b) the electrode surface layer contains an electron donor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3} and in step (f) the doped electrode layer contains an electron acceptor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

38. A method according to Claim 35 or 36 wherein in step (b) the electrode surface layer contains an electron acceptor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3} and in step (f) the doped electrode layer contains an electron donor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

39. A method according to Claim 35, 36, 37 or 38 wherein the waveguide is gold doped to reduce carrier lifetime and increase recombination site density therein.

40. A method according to any one of Claims 35 to 39 wherein lattice defects are induced in the waveguide for reducing carrier lifetime and increasing recombination site density therein.

41. A method according to Claim 40 wherein the defects in the waveguide are at least one of electron, laser or neutron irradiation induced.

42. A method according to any one of Claims 35 to 41 wherein in step (d) the bonding process comprises polishing the wafers to planarise them, bringing them into contact with one another and then heating them for a period to a temperature in a range of 800 °C to 1200 °C.

43. A method according to Claim 42 wherein the wafers are heated to the temperature in an atmosphere of wet oxygen and nitrogen.

44. A method for fabricating an optical device, the method including the steps of:

(a) providing first and second doped silicon wafers;

(b) doping the first wafer with impurity to form a electrode surface layer upon it;

(c) depositing a silicon dioxide surface layer onto the second wafer;

(d) etching selectively a channel through the silicon dioxide layer;

(e) depositing a doped polysilicon layer onto the silicon dioxide layer and into the channel;

(f) planarising the polysilicon layer by polishing it;

(g) bonding the polysilicon layer of the second wafer from step (f) to the electrode surface layer of the first wafer from step (b) by using a bonding process to form a wafer couplet;

(h) polishing the second wafer in the couplet to form a thinned doped silicon layer adjoining the silicon dioxide surface layer;

(i) doping the thinned silicon layer with impurity to form a doped electrode layer thereon;

(j) etching selectively into the doped electrode layer and the thinned silicon layer to delineate a rib waveguide therein; and

(k) etching selectively one or more via connection channels through the thinned doped silicon layer and the silicon dioxide layer for making electrical connection to the polysilicon layer.

45. A method according to Claim 44 wherein in step (a) the wafers have a dopant concentration of less than 10^{16} atoms cm^{-3}.

46. A method according to Claim 44 or 45 wherein in step (b) the electrode surface layer contains an electron donor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3} and in step (i) the doped electrode layer contains an electron acceptor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

47. A method according to Claim 44 or 45 wherein in step (b) the electrode surface layer contains an electron acceptor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3} and in step (i) the doped electrode layer contains an electron donor impurity to a concentration in a range of 10^{18} to 10^{19} atoms cm^{-3}.

48. A method according to any one of Claims 43 to 47 wherein the waveguide is gold doped to reduce carrier lifetime and increase recombination site density therein.

49. A method according to any one of Claims 43 to 48 wherein lattice defects are induced in the waveguide for reducing carrier lifetime and increasing recombination site density therein.

50. A method according to Claim 49 wherein the defects in the waveguide are at least one of electron, laser or neutron irradiation induced.

51. A method according to any one of Claims 43 to 50 wherein in step (g) the bonding process comprises polishing the wafers to planarise them, bringing them into contact with one another and then heating them for a period to a temperature in a range of 800 °C to 1200 °C.

52. A method according to Claim 49 wherein the wafers are heated to the temperature in an atmosphere of wet oxygen and nitrogen.

53. A device according to any one of Claims 1 to 11 and 17 to 34 incorporating epitaxially grown layers.

The Patent Office

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Claims searched:	1 to 34	**Date of search:**	9 June 1997

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G2F (FCE FCW)

Int Cl (Ed.6): G02F 1/025

Other: ONLINE: EDOC WPI JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0526023 A2	(NEC)-see figure 1 and column 6 line 21 to 55 and column 7 line 57 to column 8 line 13	1, 2
X	EP 0121401 A2	(SUMITOMO)-see figure 1	1, 2
X	US 4787691	(SECRETARY OF THE AIR FORCE)-see figure 1 and column 2 line 50 to column 3 line 36	1-3
X	US 4093345	(BELL TELEPHONE)-see figure 1	1, 2

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